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INVESTIGATION ON THE FLOW FIELD IN NANO-SEPARATOR CONSIDERING A FLUID-STRUCTURE INTERACTION

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Abstract. Recently, in various areas, equipments to separate and classify nano-size particles are required. However, the production and collection of nano-particles are very difficult and cost consuming with current technologies. Therefore, we have been investigating a new solid-liquid separator in order to efficiency separate nano-particles from liquid. This separator enables us to separate and classify nano-size particles by using centrifugal force and differences in specific gravity. However, the separation phenomena of particles from liquid have not been clarified yet. Therefore, the design of the separator depends only on the emprical trial and error. Hence, a numerical simulation is expected to be a useful analysis and design tool for determining the optimum shape and dimensions. A rotating screw in the separator is deformed by centrifugal force and flow drag, and thus the screw deformation may change the separation performance. Therefore, it is required to consider the screw deformation for the optimum design. In the present study, we computed the fluid-structure interaction between the screw and liquid with MPS method. The local flow field in the simplified separator that consists of a 2D rotating flat plate and a cylinder is computed to investigate the effect of the screw deformation on the flow field in the separator. It is confirmed that the flow field in the solid-liquid separator is changed by the screw deformation.

1 INTRODUCTION

Recently, in chemical, metal and environmental industries, equipments to separate and classify nano-size particles are required in order to nanomize material particles, collect microscopic particles and purify wastewater. However, the production and collection of nano-particles are very difficult and cost consuming with current technologies. For example, the conventional particle separator, which is a so-called cyclone, can separate only few-micron-size particles from liquid (Stairmand(1985), Krishna et al.(2010))[1][2], and thus it cannot be applied to nano-particles separation.

Therefore, We have been investigating a new solid-liquid separator. This separator enables us to separate and classify nano-size particles, to cut down the water content ratio of disposed particles and to accomplish extremely high collection efficiency by using centrifugal force and differences in specific gravity.

However, since the complexity of the flow in the separator prevents us from measuring and observing the flow and particle behaviors, the separation phenomena of particles from liquid have not been clarified yet. Therefore, the design of the separator depends only on the emprical trial and error. Hence, a numerical simulation is expected to be a useful analysis and design tool for determining the optimum shape and dimensions.

In addition, a rotating screw in the separator is deformed by centrifugal force and flow drag, and thus the screw deformation may change the separation performance. Therefore, it is required to consider the screw deformation for the optimum design.

In the present study, we compute the fluid-structure interaction between the screw and liquid with MPS method (Shao (2013) and Koshizuka et al. (1995)) [3][4]. The local flow field in the simplified separator that consists of a 2D rotating flat plate and a cylinder is computed to investigate the effect of the screw deformation on the flow field in the separator. It is confirmed that the flow field in the solid-liquid separator is changed by the screw deformation.

2 NUMERICAL PROCEDURE

2.1 Liquid phase

In this study, the Explicit-MPS method (Oochi (2010) and Yamada (2011)) [5][6] is used for the fluid analysis. The governing equations for incompressible Newtonian fluids in the Lagrangian frame of reference, which are conservation equations of mass and momentum, are represented by the continuity equation and the Navier-Stokes equations as follows:

$$\frac{D\rho}{Dt} = 0 \tag{1}$$

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{v} + \vec{F} \tag{2}$$

where, ρ is the density of liquid phase, P is the pressure, $\vec{v}$ is the velocity, ν is the kinematic viscosity and $\vec{F}$ is the external force.

The MPS defines differential operators as sum of interaction between two particles. In the Explicit-MPS, gradient and Laplacian operations are given by Eqs. (3) and (4).

$$\nabla\phi_i = \frac{d}{n_0}\sum_{j\neq i}\left(\frac{\phi_j + \phi_i}{\left|r_j - r_i\right|^2}\left(r_j - r_i\right)w\left(\left|r_j - r_i\right|\right)\right) \tag{3}$$

$$\nabla^2 \phi_i = \frac{2d}{n_0 \lambda} \sum_{j \neq i} \left((\phi_j - \phi_i) w(|r_j - r_i|) \right) \tag{4}$$

where, d, n_0 and r are dimension number, initial number density and position, ϕ is any scalar, and w is called a weight function and is given by Eqs. (5) and (6).

$$w(r) = \frac{r_0}{r} - \frac{r}{r_0} \qquad \text{for pressure gradient} \tag{5}$$

$$w(r) = \frac{r_0}{r} + \frac{r}{r_0} - 2 \qquad \text{for others} \tag{6}$$

On the condition that $r>r_0$, both weight functions are given by Eq. (7),

$$w(r) = 0 \tag{7}$$

where r_0 is the influence radius to compact interaction area. λ is a constant to estimate a diffusion coefficient with exact solution, and it is given by Eq. (8) in an initial condition.

$$\lambda = \frac{\sum_{j \neq i} |r_j - r_i|^2 w(|r_j - r_i|)}{\sum_{j \neq i} w(|r_j - r_i|)} \tag{8}$$

n_0 is a constant given by Eq. (9) in an initial condition.

$$n_0 = \sum_{j \neq i} w(|r_j - r_i|) \tag{9}$$

In the Explicit-MPS method, pressure is described by a function of weight density and is given by Eq. (10). The Explicit-MPS method does not need any pressure Poisson equation, so it is much faster than the conventional SI-MPS method,

$$P = \max\left(0, c^2 (\rho - \rho_0)\right) \tag{10}$$

where c and ρ_0 are sound speed and density in an initial condition. The Explicit-MPS method uses relaxed sound speed in order to take large integration time and to make computations faster.

2.2 Solid phase

The Hamiltonian MPS method (Suzuki et al. (2008)) [7] is used for the structure analysis. The governing equation is the equation of motion for elastic body as follows:

$$\rho \frac{\partial \vec{v}}{\partial t} = -\frac{\partial W}{\partial \vec{r}} \tag{11}$$

$$W = \Pi : \mathrm{F} = \mathrm{S} : \mathrm{E} \tag{12}$$

where, W is the potential energy of elastic body, Π is the first Kirchhoff stress tensor, F is the deformation gradient tensor, S the second Kirchhoff stress tensor and E is the Green-Lagrangian strain tensor. They are given by Eq. (13) to (16), respectively,

$$\Pi = \mathrm{FS} \tag{13}$$

$$\mathrm{F_i} = \left[\sum_{\mathrm{j}} \left(\frac{r_j^0 - r_i^0}{\left|r_j^0 - r_i^0\right|} \otimes \frac{r_j^0 - r_i^0}{\left|r_j^0 - r_i^0\right|} w\left(\left|r_j - r_i\right|\right) \right) \right]^{-1} \cdot \sum_{\mathrm{jj}} \left(\frac{r_j^0 - r_i^0}{\left|r_j^0 - r_i^0\right|} \otimes \frac{r_j^0 - r_i^0}{\left|r_j^0 - r_i^0\right|} w\left(\left|r_j - r_i\right|\right) \right) \tag{14}$$

$$\mathrm{E} = \frac{1}{2}\left(\mathrm{F}^T \mathrm{F} - \mathrm{I}\right) \tag{15}$$

$$\mathrm{S} = \lambda Trace(\mathrm{E})\mathrm{I} + 2\mu \mathrm{E} \tag{16}$$

where, **I** is the unit matrix and λ and μ are the Lame constants.

The acceleration of a particle is computed through the Hamilton equation (17).

$$\rho_i a_i^t = \rho_i \frac{v_i^{t+1} - v_i^t}{\Delta t} = -\sum_j \frac{\partial W_j}{\partial r_i} = -\sum_j \frac{\partial W_j}{\partial \mathrm{F}_j} \frac{\partial \mathrm{F}_j}{\partial r_i} = -\sum_j \Pi_j : \frac{\partial \mathrm{F}_j}{\partial r_i} \tag{17}$$

2.3 Fluid-structure interaction analysis

The fluid-structure interaction analysis requires the numerical procedures for both liquid and solid phases. Additionally, it is also required to take into account the collision between different structures and the interaction between fluid and structure.

The algorithm of fluid-structure interaction analysis is shown in Fig.1. Red box denotes the structure computation, blue box denotes the fluid computation, green box denotes the interaction and white box denotes the common computation.

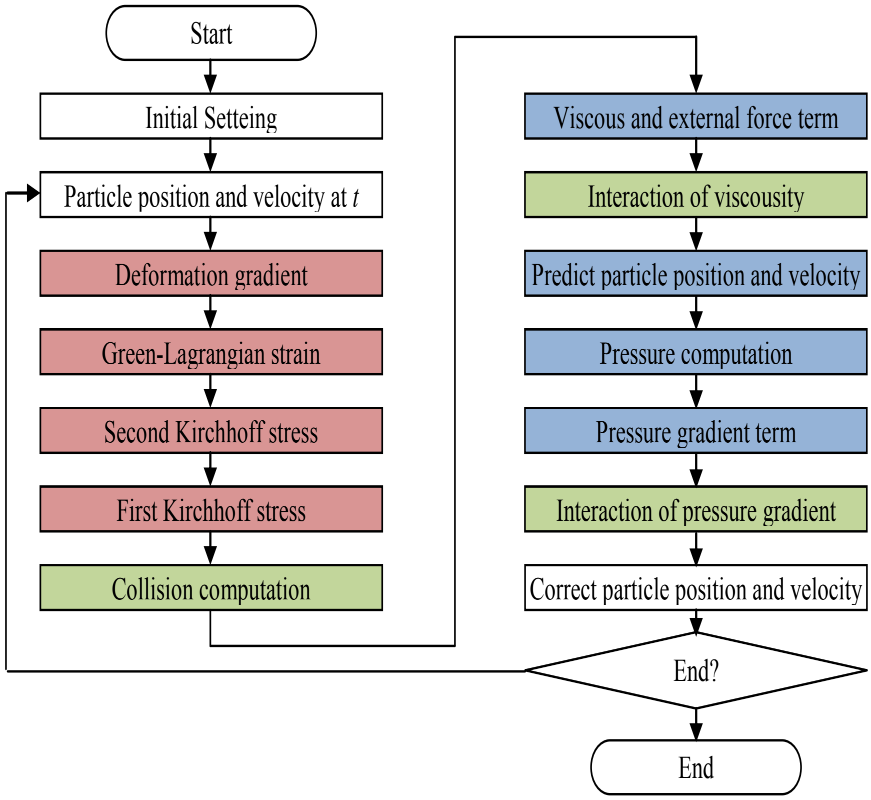
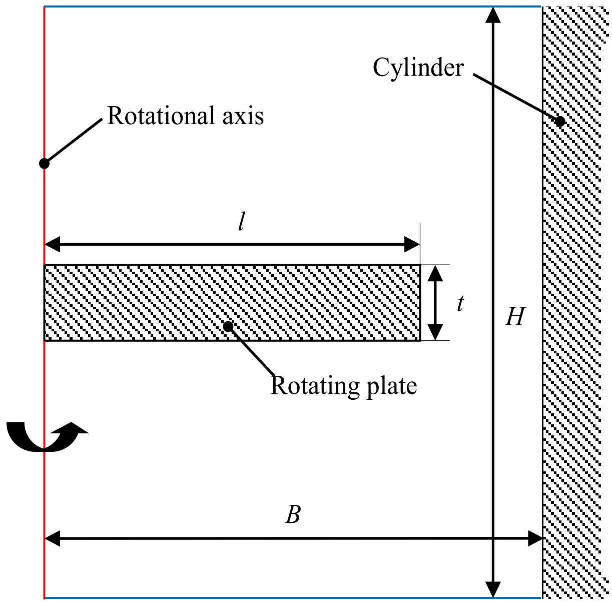


Figure 1: Algorithm of fluid-structure interaction analysis

3 COMPUTATIONAL CONDITION

In this study, the local flow field in the simplified separator that consists of a 2D rotating flat plate and a cylinder is computed to investigate the effect of the screw deformation on the flow field in the separator. In Fig.2, the computational domain is exhibited. The rotating flat plate is elastic and the cylinder is a rigid body. The rotating flat plate is deformed by centrifugal force. At initial, the computational domain is filled with liquid particle. In this figure, the red line is the inlet boundary of liquid particles and the blue one is the outlet boundary. The computational condition is listed in Table 1. The particle diameter is 0.01m, so the particle number of plate is 319 and that of cylinder is 255. The working fluid is water and the rotating flat plate is aluminium. Furthermore, the rotating speed of the plate is 3001rpm.



Dimensions of computational domain

Domain weidth	B	300 [mm]
Domain height	H	500 [mm]
Plate length	l	280 [mm]
Plate thickness	t	100 [mm]

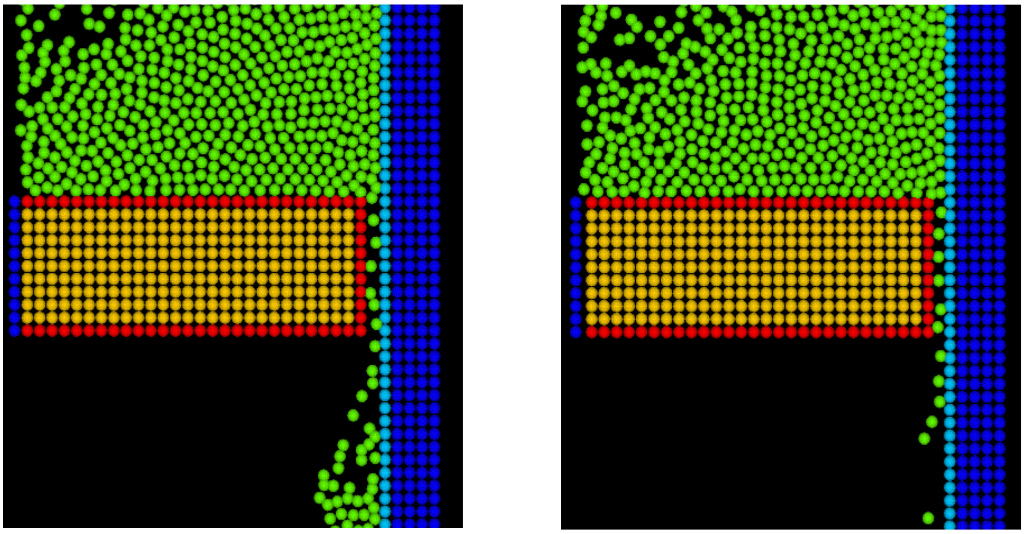
Figure 2: A schematic view of computational domain

Table 1: Computational conditions

Particles		Liquid phase(Water)		Solid phase(Aluminum)	
Diameter	0.01[m]	Density	1000 [kg/m^3]	Density	2.2×10^3[kg/m^3]
Number of plate	319	Kinematic viscosity	1.004×10^{-6}[m^2/s]	Young's modulus	70.6[GPa]
Number of cylinder	255			Poisson ratio	0.3

4 COMPUTATIONAL RESULTS

In Fig.3, computational results for no deformation case(a) and max deformation case(b) are shown. The green particles in this figure are the liquid phase (water). As Fig.3 indicates, the clearance between the rotating flat plate and the cylinder of Fig.3 (b) is smaller than that of Fig.3 (a). Therefore, the amount of liquid particles that flow downward is decreased in Fig.3 (b).In this paper, although the nano-particle in the liquid is not considered, the amount of nano-particles that flow downward may be decreased as well as liquid particles. The separation performance would be affected by the change of flow field in the separator as described above.



(a) No deformation (b) Max deformation

Figure 3: Computational results

In our presentations, the behavior of nano-particles will be shown and discussed in detail.

5 CONCLUSIONS

We computed the fluid-structure interaction between screw and liquid with MPS method. The knowledge obtained in the present study is described below.

- The clearance between the rotating flat plate and the cylinder at max deformation is smaller than that at no deformation.
  Therefore, the amount of liquid particles that flow downward is decreased at max deformation.
- The amount of nano-particles that flow downward may be decreased as well as liquid particles. So the separation performance would be affected by the change of flow field in the separator as described above.
- In our future work, we will have to compute and investigate the 3D flow field in the separator.

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